Interventional CMR

Elliot McVeigh[1], PhD, Michael Guttman[1], MS, Peter Kellman[1], PhD,
Amish Raval[2], MD, Robert Lederman[2], MD
[1]Laboratory of Cardiac Energetics,[2]Cardiology Branch
NHLBI, National Institutes of Health, DHHS

Introduction

Interventional CMR has been undergoing rapid development because of the availability of MR compatible interventional catheters, and the increased performance of the MR systems themselves. Much of this development has benefited from the previous groundbreaking work in MRI guided surgical technologies [1;2]; however, intravascular techniques do not carry the requirement for an open access scanner, and hence higher imaging performance during procedures can be achieved. Now, with the availability of a short, relatively open cylindrical scanner, high imaging performance is also available to guide direct surgical procedures. Dumoulin and colleagues [3] demonstrated real-time catheter tracking early on in the development of MRI, and interventional MRI has subsequently developed into the obvious method for delivery of numerous therapies.

Real-time Imaging

One of the principal enabling technologies for guiding interventional procedures in the beating heart is real-time imaging. The obvious trade-off is between spatial resolution and temporal resolution, but this should be fully adjustable on an interactive system. With the development of multiple receiver systems, image acquisition can be accelerated using surface coil arrays.

Accelerated Imaging Methods

The position of the heart in the center of the body makes it an ideal imaging target for the application of "reduced field of view" accelerated imaging techniques such as SMASH[4], SENSE[5], and GRAPPA[6]. Also, because we are imaging a time sequence we can also employ temporal acceleration techniques such as TSENSE[7], UNFOLD[8] and kt-BLAST. These methods, other that UNOLD and kt-BLAST, exploit the difference in sensitivity profiles between individual coil elements in a receive array to reduce the number of gradient encoding steps required for imaging. The methods of UNFOLD and kt-BLAST exploit the fact that only a fraction of the field of view is changing in time. Standard production MR systems are now available with up to N=32 channels, enabling robust performance with acceleration rate R=4 in a single dimension.

The parallel imaging reconstruction assumes that the coil sensitivity profiles are known or can be estimated. A key area of current research has been on auto-calibration methods for estimating the in-vivo coil sensitivities [9], [6], [10], [7]. For real-time dynamic imaging applications, the adaptive TSENSE method [7] provides a means of automatic update which is useful for interventional MR application in which the scan plane orientation can be changing dynamically. Parallel imaging image reconstruction has been implemented in real-time with low latency using a software based multi-threaded implementation [11].

Real-time Interactive Scanner Control

The ability to interactively modify pulse sequence and display parameters during a scan is essential for an interventional procedure. For example, in a procedure requiring catheter-based delivery of a therapeutic agent to a precise target, an initial large FOV can be used to visualize and active catheter superimposed as color highlighted signal. The physician can intermittently turn off slice selection to see the whole catheter (including portions which are outside the imaging plane), then reduce the FOV when nearing the target. Saturation or other contrast change may be turned on to visualize delivery of the agent, and high resolution images can be obtained to visualize the result of the delivery (i.e. the shape of a burn, or shape of an injection). Multiple imaging planes may be imaged and interactively adjusted during the scan to allow simultaneous views of the current catheter position and the target. Imaging planes can be interactively turned off to increase the temporal resolution in the remaining planes.

The development of the appropriate user interface for interventional CMR is ongoing. The first systems allowed basic real-time imaging with a single adjustable imaging plane [12;13]. Subsequent systems added many of the features described above [14-18]. Automatic image parameter adjustment in response to motion of a device being tracked has also been investigated[19;20].

Some MR scanner manufacturers provide an interactive interface for adjusting imaging planes and some parameters during a real-time scan. These products also typically provide features for saving streams of images, book marking, pausing, and limited changes to image contrast, such as turning on a saturation pulse. In some cases, device tracking is also available.

Interventional Devices

Passive Devices

Catheters can be located in the imaging volume using the contrast obtained from the distortion or loss of signal caused by the catheter[21]. Catheters filled with contrast agent such as Gd-DTPA can highlight the device with bright signal[22], but the device can still exit the imaging plane, causing the loss of the location of the tip. The principal advantage of passive devices is the fact that there is no concern about generating unwanted heating. A very successful application of a passive device is the CO_2 filled balloon used by Razavi et. al. [23], which has also been used by Kuehne et. al. to obtain right ventricular PV loops [24].

Active Devices

Serfaty demonstrated that active guidewires could be used to position devices under MRI guidance [25] and projection angiography could be performed [26] and recently Omary and colleagues have demonstrated performing coronary catheterization on 12/12 swine with an active guidewire [27].

A Stelleto (Boston Scientific, Natick, MA) injection catheter has been modified to act as two separate coils: one in the shaft of the catheter, and the other localized to the tip. These two coils can be connected to their own channels in the receiver. This device was used to target the injection of mesenchymal stem cells in the border zone of infarcts[28]. A similar injection catheter design has been implemented by Karmarkar and colleagues [29]. Zuehlsdorff and colleagues have made an active catheter with the ability to switch between a set of loops on the shaft of a catheter and a single small coil located at the tip[30].

Safety is an issue with *any* device that is electrically active; a considerable effort has been focused upon the potential of conducting devices to generate unwanted heating in the tissue[31-39]. For wide use in humans electrically active devices will need to incorporate cables in which the currents are eliminated by rf chokes incorporated into the cable [40;41]. Quick and colleagues have implemented a catheter device in which a resonant coil is imbedded, but this coil is *not* electronically connected to the scanner [42]. The signal amplitude is amplified around the imbedded coil by inductive coupling between the imbedded coil and the receiver coil on the body surface.

Interventional Procedures

A host of applications are currently being developed with real-time MRI guidance; this section lists a *few* of these applications.

Electrophysiological ablation is an outstanding target for interventional CMR. Real-time display of the catheter position on 3D-MRI has been shown to be useful for anatomically targeted catheter navigation and subsequent radio-frequency ablation in the IVC, the fossa ovalis, and the left atrium [43]. Preliminary catheter tracking with acquisition of filtered local electrograms has been reported[33], as has MRI characterization of ablated myocardium[44]. The use of real-time interactive MRI for full real-time guidance of these procedures will also allow the physician to monitor the size of the lesion immediately after RF application. This will make the procedure faster, safer and likely more effective.

Schalla *et al* have demonstrated transvenous and transarterial cardiac catheterization in a porcine model of atrial septal defect wholly using SSFP rtMRI and tracking receiver microcoils to mark the catheter tips[45].

Percutaneous transcatheter myocardial injection of gadolinium injectate[46], and the targeted delivery of iron-labeled mesenchymal stem cells to specific myocardial infarct targets[28] have both been reported. These injection applications used multiple active intravascular devices with 3d volume rendering of multislice acquisitions, with color highlighting of catheter-related signal. Also, retrograde transaortic access has been used to perform image-guided myocardial injections[29;47].

MRI guided transcatheter aortic valve replacement in swine using passive nitinol devices has been achieved by Kuehne et al[24]. This application is attractive because of the critical importance of image-guided placement of the stent-valve in relation to the coronary arteries and aortic root.

Several groups[48;49] have performed percutaneous coronary artery intervention in healthy animals, and demonstrated images of intracoronary stent artifacts[48].

Vascular Interventions

Several groups have conducted angioplasty[50 51 52 53;54] and stenting [55-60] using passive and active catheter techniques in animal models of arterial stenosis. Also, aortic aneurysm endografts[61;62] and inferior vena cava filter[63-65] devices have been placed, and embolization of renal artery segments[66;67] has been achieved.

Recently, Ravel et al[68] have recanalized long segments of chronic total arterial occlusions in an animal model. Using custom catheter and guidewire coils, they were able to traverse long segments of occlusion while keeping within arterial adventitial borders, an important clinical challenge. Weiss *et al*[41] have made a transcatheter "mesocaval shunt," or extrahepatic connection between portal and venous circulations, first using a septostomy needle and later using a novel custom vascular connector. Kee *et al* integrated a flat-panel XRF system in a double-doughnut operative MRI system and conducted multimodal transjugular intrahepatic portosystemic shunting (TIPS) in animals[69] and in patients and showed a significant reduction in number of punctures required.

A few interventional CMR procedures have been conducted in humans. Razavi et al.[23] reported a landmark series of cardiac catheterization performed successfully children using a combined XMR environment. The Regensburg team has conducted high quality selective intra-arterial MR angiography[70] and has reported some preliminary revascularization procedures using passive devices in the iliac[21] and femoral[70] arteries.

Future Directions

The procedures which will benefit the most from MRI guidance are those which are improved by immediate visualization of the effect of treatment. This is particularly obvious for ablation techniques, targeted injections, and vascular treatments in which the nature of the flow in a vessel is vital information. The technologies which are in critical need at this time are catheter based instrumentation which is MRI compatible. To date, there has been little interest from catheter manufacturers in developing these tools for the simple reason that they will not sell very many in the next few years. This means that demonstration of the benefits from these technologies and procedures will be principally due to the efforts of independent laboratories.

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